Studying the kinematics of faint stellar populations with the Planetary Nebula Spectrograph

Michael R. Merrifield[*] and The PN.S Consortium[†]

[*]*School of Physics & Astronomy, University of Nottingham, UK*
[†]*http://www.astro.rug.nl/~pns/*

Abstract. Galaxies are faint enough when one observes just their light distributions, but in studying their full dynamical structure the stars are spread over the six dimensions of phase space rather than just the three spatial dimensions, making their densities very low indeed. This low signal is unfortunate, as stellar dynamics hold important clues to these systems' life histories, and the issue is compounded by the fact that the most interesting information comes from the faintest outer parts of galaxies, where dynamical timescales (and hence memories of past history) are longest.

To extract this information, we have constructed a special-purpose instrument, the Planetary Nebula Spectrograph, which observes planetary nebulae as kinematic tracers of the stellar population, and allows one to study the stellar dynamics of galaxies down to extremely low surface brightnesses. Here, we present results from this instrument that illustrate how it can uncover the nature of low surface-brightness features such as thick disks by studying their kinematics, and trace faint kinematic populations that are photometrically undetectable.

INTRODUCTION

Because stars are well-spaced, even the inner parts of galaxies can appear faint, comparable in surface brightness to the darkest of night skies. Not surprisingly, then, when we start exploring the full six-dimensional phase space of velocities and positions that stars occupy in galaxies, the signal per phase space element becomes almost vanishingly small. In the case of the Milky Way, for example, the fascinating stellar streams in the halo [1] have widths of only $\sim 20\,\mathrm{pc}$, and velocity dispersions of maybe $\sim 10\,\mathrm{km\,s^{-1}}$. If we were to divide the Galaxy, with a linear dimension of $\sim 20\,\mathrm{kpc}$ and velocities spanning $\sim 600\,\mathrm{km\,s^{-1}}$, into resolution elements this small, we would end up with $\sim 10^{14}$ of them, many more than there are stars in the Milky Way, so the average occupation number per element would be very small indeed.

Thus, if we are to study the detailed kinematics of galaxies, we need to do two things. First, we must be able to detect stellar populations at extremely low phase densities, which essentially means detecting individual stars. Second, we need to come up with ways to combine the information from these individual detections in order to bring together enough signal to say anything about the properties of the galaxy, and hence reconstruct its detailed dynamical structure in order to learn about its evolution.

Planetary nebulae (PNe) offer an ideal tracer of such faint stellar populations, as

they are readily individually detectable from their emission lines, even in quite distant galaxies, and the Doppler shifts in these lines can be used to measure their line-of-sight velocities. To make such measurements efficiently in a single step, we have designed and built a customized instrument, the Planetary Nebula Spectrograph or PN.S [2]. In this paper, we present examples from a couple of the projects that we have been undertaking with this instrument, to illustrates the principles of investigating galaxies in the ultimate low-density regime of phase space.

THE THICK DISK IN NGC 891

When one traces edge-on stellar disks away from the plane out to very low surface brightnesses, an excess of light above the extrapolation of the normal disk population is frequently found [3]. The nature of such "thick disks" remains highly controversial: they could just be the extreme tail of the normal disk population, or they could represent some more dramatic event, such as the debris from a merger. One exciting new clue to help distinguish between these possibilities was uncovered when it was found that the thick disk in the edge-on system FGC 227 appears to be rotating in the opposite direction to the normal thin-disk population, indicating that it would have to be a distinct component such as might be formed in a merger [4]. However, the surface brightness of this component is so faint that, even with ten hours of integration on an 8-metre telescope, conventional spectroscopy had such large error bars that the data were also consistent with co-rotating thin and thick disks.

As Figure 1 illustrates, we can do a great deal better with a rather shorter integration on a 4-metre telescope using PN.S. The upper panel shows the number counts of PNe detected in the edge-on spiral NGC 891 as a function of distance from its plane. The lines show a possible decomposition of the disk into thin and thick exponential components [5]. The data drop below the model close to the plane, as PNe are difficult to detect against the high surface brightness of the galaxy in this region, and some PNe will also be lost in NGC 891's strong dust lane. However, in the region we are interested in away from the plane, the PN number counts trace the light distribution very well, underlining their nature as generic tracers of the stellar population. Further, we are clearly detecting them in significant numbers out to beyond the transition where the thick disk becomes the dominant component.

The lower panel in this figure shows the observed mean rotation speed for these PNe as a function of distance from the plane. There is plenty of signal to distinguish between co- and counter-rotating thin and thick disk components, and in this system the two are clearly rotating in the same direction. Indeed, we can go further and fit a simple single-component kinematic model to the data. This heuristic model is of the form

$$\langle v \rangle = \alpha(v_c - \beta\sigma_z(z)^2/v_c), \tag{1}$$

where α provides the factor that allows for the line-of-sight projection effects that reduce the line-of-sight velocity below the mean rotational velocity [6], while β parameterizes all the terms related to the shape of the velocity ellipsoid in the asymmetric drift equation [7]; here it is assumed to be a constant. The circular speed of the galaxy, v_c, can be inferred from gas kinematics, while the vertical velocity dispersion, $\sigma_z(z)$, is estimated
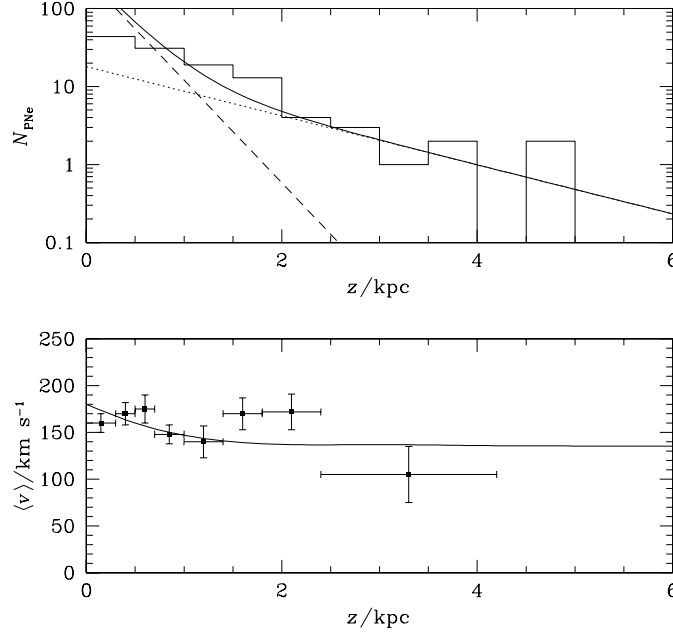
FIGURE 1. Properties of the PNe in the disk of the edge-on galaxy NGC 891 as a function of distance from the galactic plane. The upper panel shows the number counts of PNe as detected with PN.S, with lines showing a model decomposition of conventional photometry into thin disk and thick disk [5]. The lower panel shows the mean rotation velocity of these PNe, with a line showing the simplest possible single-population model for their kinematics.

by solving the Jeans equation for a self-gravitating sheet whose density distribution is given by the double exponential model in the upper panel of Figure 1. Clearly, the data are essentially consistent with this simple single-component model: there is no kinematic evidence that the thick disk in NGC 891 is in any way a distinct entity.

A FAINT KINEMATIC POPULATION IN M31

As a further illustration of the way in which faint kinematic components can be detected, Figure 2 shows the results of an analysis of the 2615 PNe that were found using PN.S in a survey of M31 [9]. In an inclined disk system like this, the phase space is essentially reduced to four dimensions, two spatial and two velocity. We can measure three of these components, two spatial and the line-of-sight velocity, so each PN has only one unknown coordinate. Thus, while one cannot measure the energy and angular momentum of any single PN, there is only a one-dimensional family of possibilities, as illustrated by the line sections in the figure. If group of PNe share a common orbit (and hence energy and angular momentum), then their lines will all intersect at a single point, creating a local excess in this plane. Such an excess of crossing lines is, indeed, found in this figure, at the point indicated by the box. The location of the orbit to which it corresponds does not appear in any way special in an optical image of M31, but, as the inset image in the
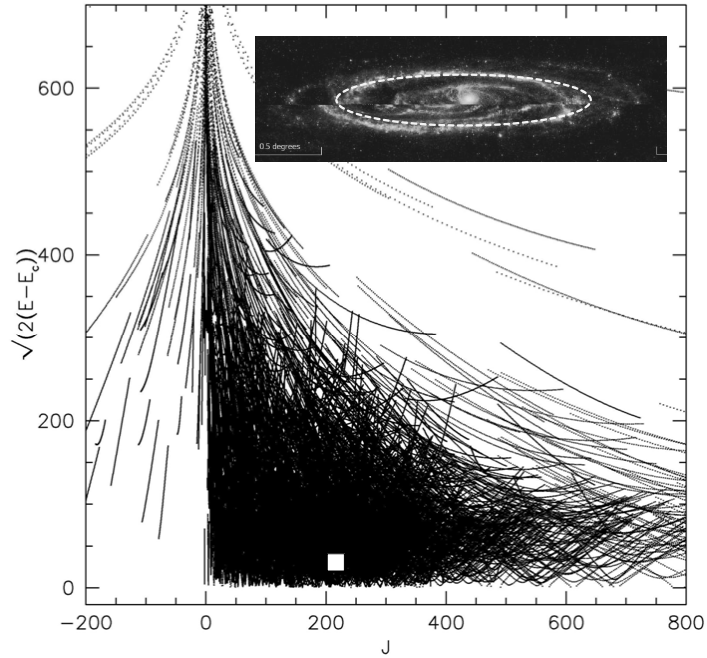
FIGURE 2. Plot of the possible values of angular momentum and energy (with the local circular energy subtracted, so a circular orbit lies at the bottom of the plot) for each of the PNe in the M31 survey data. The white box shows the point of the largest local excess of PNe. The inset shows the orbit to which this point corresponds, superimposed on a mid-infrared image of the galaxy [8].

figure shows, mid-infrared data reveal a bright ring of emission at this radius, indicating that it lies at one of the major orbital resonances. Thus, either we have detected the population of stars born in this ring of star formation, or, more likely since PNe come from old stars, we are picking out the relatively small population of objects that have become dynamically trapped at this resonance. Whatever their origin, these data again illustrate the power of PN.S to identify kinematic components that are at far too low a density in phase space to be detectable by more conventional means.

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